Signal Progress

Steven N. Stitzer

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When Privates George Elliott and Joseph Lockard discovered a large fleet of airplanes approaching Pearl Harbor, Hawai'i, on the morning of 7 December 1941, they were operating a new U.S. Army Signal Corps radar that used the same antenna for transmitting and receiving RF energy [1]. RF engineers had to quickly develop a variety of new techniques to keep the multikilowatt transmitter signals from degrading or damaging the sensitive receivers in those early systems. This past December marked the 75th anniversary of that event. Tying in with the exhibit of related hardware at the IEEE Microwave Theory and Techniques Society's (MTT-S) 2017 International Microwave Symposium in Honolulu this June, the goal of this article is to highlight some of the components and circuits used for transmit–receive (T/R) switching in U.S. radars from the pre-World War II era through the following few decades.

My first boss, Harry Goldie, liked to describe a radar as a receiver protector surrounded by some auxiliary components such as a transmitter, an antenna, and a receiver. Modern radar systems are frequently designed around phased arrays containing T/R modules using low-power junction circulators or solid-state switches. Transmitter power is distributed across a large number or elements, so each module sees only a small fraction of the total power. The designers of the earliest practical radar systems used several different

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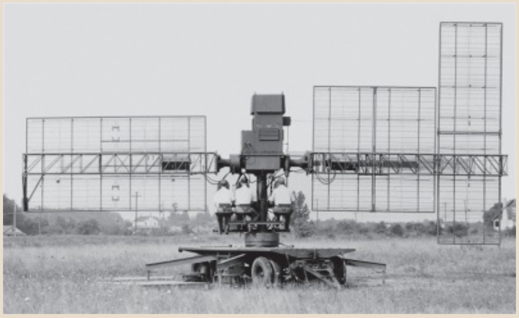

SCR-268 (US Army)

Figure 1. *An SCR-268 radar, showing separate antennas for transmitting and receiving. Note the three operators on the platform. (Photo courtesy of the U.S. Army.)*

techniques to connect their high-power, single-point transmitters and receivers to their antennas. The problem, of course, was protecting the sensitive receiver from the high power leakage of the transmitter. The required speeds of a few microseconds or less for T/R switching precluded the use of any kind of mechanical switch, and semiconductor switches were decades in the future.

Early Radars

The first practical radars were bistatic; that is, separate antennas were used for transmitting and receiving. In the British Chain Home system (or AMES) operating between 20 and 55 MHz, for example, the transmitting antennas were strung between 360-ft towers. The system had a peak transmitter power of more than 350 kW. The receiving antennas were on 240-ft towers located a few hundred meters away. At that separation, direct pickup of the transmitter signal was low enough to avoid damage, but the transmitter signal was strong enough to blank the receiver for targets closer than about 5 mi [2].

The SCR-268

The U.S. Army Signal Corps's first fielded system, the SCR-268, was used primarily for steering searchlights toward target aircraft at relatively short range [3]. It employed three separate antennas, steered together in elevation, that were mounted on a single platform, steered in azimuth (see Figure 1). One antenna was for transmitting, one was for receiving in a narrow azimuth beam, and the third was for receiving in a narrow elevation beam. Three human operators riding on the moving platform controlled the mechanical scanning and read out the target's range, elevation, and azimuth on three separate oscilloscopes. (See "Plan-Position Indicator Display.")

The system used a lobe-switching technique to enhance the accuracy of the measured target elevation and azimuth. Each receiving antenna had two outputs that were fed to two separate inputs on two separate receivers. The first two tubes were turned on and off alternately by a square-wave bias voltage applied to the grids. The two tube outputs were combined into a single signal that carried the lobe-switched waveform through a mixer, an intermediate-frequency (IF) amplifier, and finally to a video detector. The SCR-268 ran at 205 MHz, with an output of 75-kW peak power supplied by a ring oscillator comprising 16 Eimac 100TS (VT-127A) triodes. The system achieved adequate T/R isolation by virtue of the physical separation of the antennas. (See "Vacuum Tubes" for an overview of vacuum tube technology.)

The SCR-270

The Signal Corps's SCR-270 radar (one of which famously detected the large fleet of planes attacking Pearl Harbor in 1941) operated at 110 MHz and used a single antenna (see Figure 2). Besides the size reduction, a single antenna has the advantage of perfectly aligning the transmitting and receiving patterns.

The SCR-270 was designed as a search radar with a range of about 200 mi. The transmitter used a pair of Westinghouse WL-530 water-cooled triodes developed specifically for this system. Two tubes produced up to 200-kW peak power in a push–pull oscillator circuit [4], [5]. The transmitter and receiver were connected directly to the antenna through transmission lines, the phase lengths of which were chosen to minimize the transmitter power reaching the receiver. The first line of receiver protection was an air spark gap placed across the open-wire, twin-lead transmission line leading to the receiver. When the transmitter pulsed, leakage power broke down the spark gap, partially shorting the transmission line and thereby preventing most of any high-power RF from the transmitter reaching the receiver. This air spark gap was followed

Plan-Position Indicator Display

Early radars usually had a simple single-axis oscilloscope display showing the transmitter pulse and echoes versus time. The plan-position indicator display gave a radial display of the distance to targets, which appeared as bright spots on a rotating trace synchronized with the rotating antenna. This gave a two-dimensional view of targets in all directions around the radar.

Vacuum Tubes

World War II-era electronics depended on vacuum electron devices for amplification and rectification (Figure S1). A hot cathode emitted electrons that traveled toward a positively charged anode. A cathode together with an anode produced a diode that conducted current in only one direction. The electron flow could be controlled by a wire grid placed between the cathode and the anode (1906). A small change in the voltage applied to the grid produced a large change in anode current, yielding amplification. Triodes had a single control grid. Tetrodes (ca. 1919) added a positively charged screen grid between the control grid and the anode to provide electrostatic shielding that reduced internal feedback. Pentodes (ca. 1928) had a third grid between the screen grid and the anode to reduce the effect of secondary emission from the anode. Most tubes had a coaxial construction with the cathode at the center. Early vacuum tubes usually had long wires leading from the elements inside a glass envelope to a plug-in base. For high-frequency operation, reduction of lead inductance and interelectrode capacitance was critical. Acorn tubes (so named for their shape) that minimized the length of the leads were developed in the mid-1930s. They found use up to a few hundred megahertz. Lighthouse (also named because of their shape) or disk-seal tubes were developed in the early 1940s. They used a planar structure that could be plugged directly into a resonant cavity and were useful to about 3.5 GHz. Also see the references in Table 1.

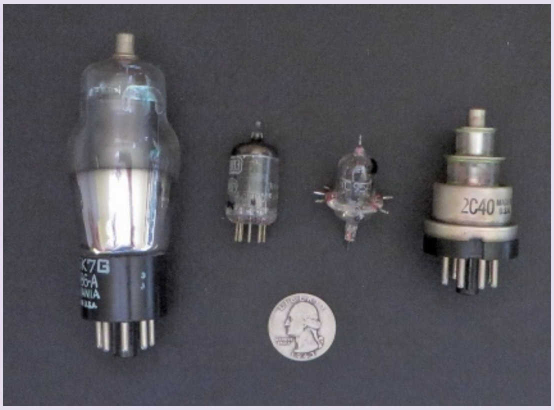

Figure S1. *Conventional (6K7G), miniature (9003), acorn (954), and lighthouse (2C40) RF amplifier vacuum tubes.*

by a second spark gap enclosed in a sealed, gas-filled glass tube connected directly across the receiver input terminals, as shown in Figure 3. The low-pressure gas fill could be ionized ("fired") at a lower power than the air-filled gap.

The first gas spark-gap tubes for the SCR-270 were developed and handmade by the Signal Corps's Harold Zahl [6]. (Zahl had been investigating RF-driven gas discharges since at least 1933 [7].) A refined version, the WL-532 or 1B32, designed and manufactured by Westinghouse, was first used in the SCR-270-D in 1942 (see Figure 4). Despite the use of these protective devices, the RCA receiver designers chose as the first tube in the receiver an 832 10-watt twin-tetrode very-high-frequency transmitting tube. At high RF input power, grid rectification produced a negative voltage

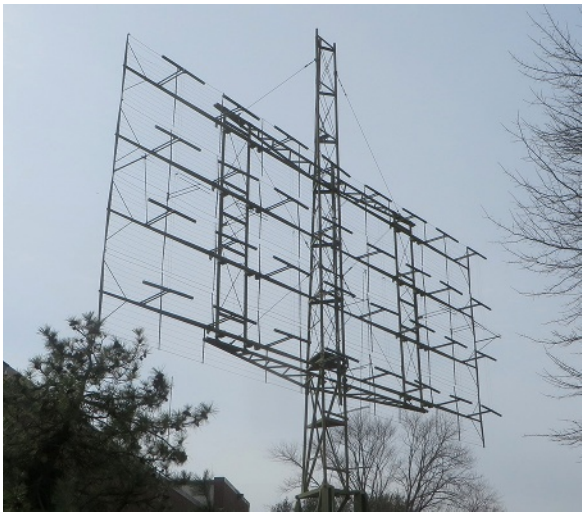

Figure 2. *A monostatic SCR-270-D antenna, located at the National Electronics Museum, Linthicum, Maryland, in a 2017 photo by the author.*

Figure 3. *The SCR-270 display and receiver setup (reproduction) at the National Electronics Museum. A GA-4 spark-gap T/R tube was mounted across the twin-lead input transmission line atop the BC-404 receiver (inset). (Photo by the author, 2016.)*

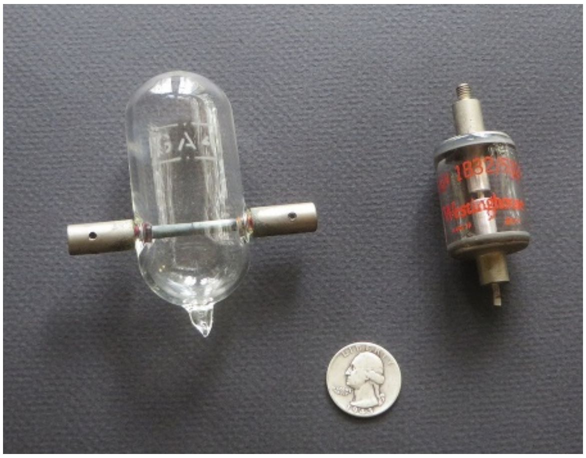

Figure 4. *GA-4 spark-gap tubes (example on the left) used in early versions of SCR-270 radars were replaced by WL-532/1B32 spark-gap T/R cells (example on the right) in later versions. The GA-4 had tungsten electrodes that sputtered metal on the inner walls of the tube during operation, gradually causing increased insertion loss. The tube also contained a small amount of powdered tungsten. The sputtered metal was supposed to be cleaned periodically by vigorously shaking the tube manually. (Photo by the author, 2016.)*

that biased the tube off during the transmit pulse. The second stage was an RCA 1630 (A-5588) orbital beam amplifier tube (see the references in Table 1). This was followed by an acorn tube mixer and four stages of IF amplification at 20 MHz. The estimated noise figure of this lineup was approximately 14 dB. (See "World War II-Era Radar Receiver Protection Requirements" and "Plasma Frequency.")

The receiver in later-generation SCR-270s used a miniature diode-connected 9002 triode, connected across the input to act as a passive shunt limiter. This

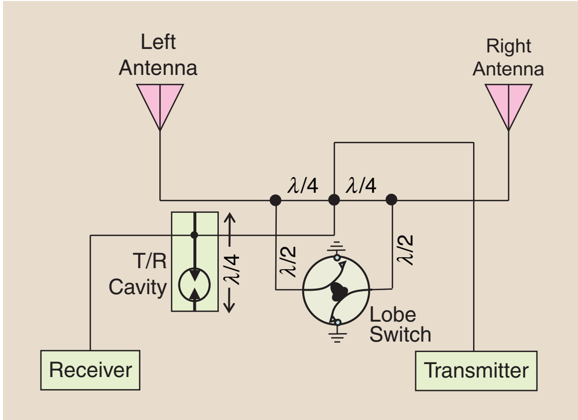

Figure 5. *A simplified schematic of an ASB radar. With the motor-driven rotary lobe switch in the position shown, the shorted side reflects a short through a half-wavelength line to the transmission line leading to the right antenna. The open side reflects an open to the left-side feed, thus enabling the left-hand antenna. On transmit, the spark-gap tube in the coaxial T/R cavity acts like a short, blocking RF from reaching the receiver. It is spaced from the antenna feed lines so as not to interfere with the transmitted power. On receive, the T/R tube acts as an open, allowing the echo signal from the left-hand antenna to travel to the single receiver. The video signal coming from the receiver is likewise simultaneously steered to the left or right in the operator's CRT display [after 9].*

was followed by two GL446A lighthouse-tube RF amplifier stages, a 6J6 twin-triode mixer, and four stages of IF amplification at 36 MHz.

ASB Series Radar

Higher frequencies were needed to reduce the size of radar antennas for aircraft. One early U.S. aircraft radar was the Navy's ASB series (see Figure 5). ASB radars operated at around 500 MHz with a peak power of approximately 5–10 kW, supplied in some versions by four Eimac 15E triodes in a push–pull parallel power oscillator circuit. This system had two antennas at the nose of the aircraft, but they were not used in a bistatic arrangement. Instead, the system switched back and forth between the two antennas approximately 30 times

World War II-Era Radar Receiver Protection Requirements

Typical specifications for point-contact mixer diodes:
Mixer loss: 5.5-8.5 dB @ 3 GHz, 6.5-10 dB @ 9 GHz
Noise figure: 11-16 dB @ 3 GHz, 13-17 dB @ 9 GHz
Burnout power: 1 W CW
Burnout pulse energy: 0.3–2 erg @ 3 GHz, 0.2–0.4 erg @ 9 GHz
Typical T/R specifications:
Insertion loss: high Q: 1.2–1.4 dB, bandpass: 0.4-0.5 dB
Leakage levels: high Q: 10-40 mW, 0.02–0.05 erg spike bandpass: < 30 mW, 0.1 erg
Recovery time to 3 dB above insertion loss: 4-7 μsec, measured at 50 kW @ 3 GHz, 10 kW @ 9 GHz
Arc loss (absorbed power): < 1 dB
Typical operating life: 250–1,000 h
[Rad lab 15 §8.5][Rad lab 16, §2.21][Rad lab14 §6.2]

Plasma Frequency

The dielectric constant of a plasma or ionized gas at frequency f is $\varepsilon = 1 + [1 - (f_p/f)^2]^{1/2}$, where the plasma frequency $2\pi f_p = (n_e q_e^2/\varepsilon_0 m_e)^{1/2}$. Here, n_e is the electron density, q_e and m_e are the electron charge and mass, and ε_0 is the permittivity of free space. If the gas is sufficiently ionized, the plasma frequency can be made to exeeed the signal frequency, the dielectric constant becomes complex, implying a complex propagation constant, and the plasma becomes reflective.

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per second, alternately transmitting and receiving for a short time on each antenna. The operator's display showed both returns as left and right horizontal deflections of vertical traces on a single cathode ray tube (CRT).

Distance was indicated by the vertical height of the trace. The left and right pips were equal in amplitude when the plane's two antennas were aimed directly at the target. The left–right switching was accomplished by a motor-driven rotary switch running at 1,800 r/min. Separate cams affixed to the common motor shaft were used to mechanically switch the T/R and video display signals, thus keeping everything synchronized. The transmitter used a free-running, self-pulsing grid-blocking circuit; the left–right switching was not synchronized to the radar pulses. T/R switching and receiver protection were accomplished with a single RCA 1960 spark-gap tube. Figure 6 shows the switch and transmission-line arrangement.

Early ASB systems used acorn tubes in the superheterodyne receiver front end; later versions used the then newly developed General Electric lighthouse tubes for improved sensitivity. Some 24,700 of these systems, manufactured by Westinghouse, Bendix, RCA, and Philco, were fielded during World War II [8].

Shipborne Radars

The U.S. Navy had been developing shipborne search and fire-control radars at 700 MHz such as the CXAS since the late 1930s [10]. The use of a single antenna for transmitting and receiving was imperative for shipboard use. In 1936, Robert Page of the U.S. Naval Research Laboratory (NRL) developed a duplexer based on transmission-line coupling and the behavior of a pair of gridded tubes at the receiver input [11]. The transmitter and receiver were connected to a single antenna through a half-wavelength transmission line shorted at its midpoint. On receive, the negatively biased grids presented a high impedance to the duplexer receiver port, and the tubes were able to amplify the low-power, common-mode echo signals. When subjected to high power during the transmitter pulse, the grids became biased positive, and the tubes then presented a very low input impedance at the receiver port. This reflected most of any high-level energy away from the receiver and back through the half-wavelength transmission line to the antenna.

By 1940, the Navy had deployed the Navy Radar Equipment Mark 1 (manufactured by Western Electric) based on this design [10]. Produced by a pair of WE-388 doorknob tubes, transmitter power at these frequencies was limited to about 2-kW peak. The British revealed the cavity magnetron developed by Boot and Randall at the University of Birmingham to U.S. and Canadian workers during the 1940 Tizard mission [12]. This breakthrough produced high enough power at microwave frequencies to make radar practical at much shorter wavelengths. The first experimental cavity magnetrons produced about 400-W peak power at 3,000 MHz, soon reaching some 15-kW peak power in the practical device that was shown to the North Americans.

Next-Generation Radar

However, the other hardware required to make a full radar system at such high frequencies was yet to be developed. The first production cavity magnetrons, manufactured by Western Electric, were scaled down in frequency (by using larger cavities) to 700 MHz to enable their use in a transmitter upgrade to the Mark 1. The tubes are compared in Figure 7. The new Radar Equipment Mark 3 was first deployed in October 1941 with transmitter power increased to 40-kW peak, boosting the radar's range by three to five times. The Mark 3 also used a motor-driven capacitor in the antenna feed to implement a lobe-switching technique for improved bearing accuracy.

Western Electric developed a series of gas discharge T/R tubes to handle these higher power levels based on concepts developed at NRL [13]. Several examples are shown in Figure 8. Key design parameters of all T/R devices are low firing and leakage power to ensure that the receiver is protected from the transmitter power reflected to the receiver by imperfect matching at the antenna or from high-level energy coming from external sources. The switch has to turn on very

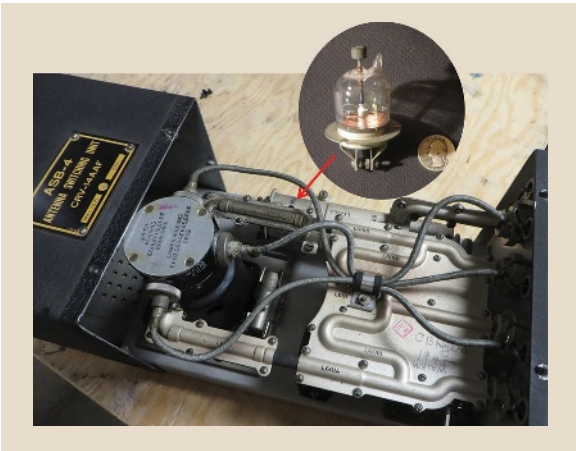

Figure 6. *ASB duplexer coaxial transmission-line outer conductors were formed from stamped metal. The motor-driven rotary switch is visible at left. The inset shows the location of the 1960 T/R tube in the coaxial cavity. (Photo by the author, 2016.)*

ASB radars operated at around 500 MHz with a peak power of approximately 5–10 kW, supplied in some versions by four Eimac 15E triodes in a push–pull parallel power oscillator circuit.

quickly to respond to the fast transmitter pulse, but it also has to turn off quickly to re-enable the receiver for close-in targets. It was found that a gas plasma discharge device fulfilled these requirements. Firing and leakage power are determined by the geometry of the electrodes and the specific gas fill. The tubes illustrated in Figure 8 contain a pair of cone electrodes that connect to an external resonant cavity via copper rings that pass through the glass walls of the tube. On application of high power at the resonant frequency of the cavity, the high RF voltage at the cone tips causes the enclosed gas to ionize.

A design feature that helped to ensure fast turn-on was a ready source of free electrons to help initiate ionization under the application of high-power RF. To this end, a weak continuous dc discharge inside the tube was created by applying several hundred volts to a so-called keep-alive electrode placed close to the cone tips. The discharge was kept at a high enough level to ensure solid firing but at a low enough level to avoid attenuating weak echo signals between radar pulses. The continuous discharge contributed to a relatively short lifetime for these T/R tubes due to erosion of the keep-alive electrode. Radioactive sources were also used to provide electrons, including naturally occurring radium (half-life ~1,600 years) and the man-made isotope cobalt-60 (half-life ~5.27 years).

With no suitable tube mixers or detectors available at the higher frequencies, microwave radar receivers used crystal diodes as mixers, which were more susceptible than tubes to burnout from exposure to high power. (See "RF Diodes.") Figure 9 shows one general scheme for waveguide duplexers using gas plasma T/R tubes. One T/R cell is mounted in a stub off the main waveguide. A second T/R cell is mounted across the waveguide leading to the receiver. When the transmitter pulses, the gas in both cells ionizes, making them act as RF short circuits.

The first cell, the anti-T/R (AT/R), electrically closes the opening in the waveguide stub, allowing RF to continue toward the antenna. The second cell, or T/R, located one half wavelength from the main waveguide, closes the second sidewall opening. This allows the transmitter RF to flow to the antenna and also blocks RF from entering the receiver. After the transmitter pulse ends, both cells deionize. Any reflected target energy coming from the antenna traveling toward the transmitter sees an open at the AT/R branch and is reflected. The T/R switch, now being deionized, allows the echo to pass to the receiver.

Many versions of the gas-discharge T/R tube were developed for waveguide. Figure 10 shows the schematic

Figure 7. *Two WE-388 doorknob tubes (left) produced about 2-kW peak power at 700 MHz in the Navy Radar Equipment Mark 1. They were replaced by 700 series cavity magnetrons, a scaled-up version of the British E-1189. Shown here without the magnet, they generated up to 40-kW peak power in the 680–720 MHz range in the Mark 3 radar. (Photo by the author, 2016.)*

Figure 8. *Typical T/R tubes: from left, the Western Electric 702A for coaxial transmission lines (0.6–1.5 GHz, used in CXAS radar), Western Electric 709A (used in SJ radar), and Bomac 721B (used in SCR-584 S-band radar). (Photo by the author, 2016.)*

RF Diodes

Early microwave receivers used point-contact or cat-whisker diodes as detectors or mixers. When used as receiver protectors, P-N junction and Schottky diodes rectify an RF waveform, acting like a clipper. A PIN diode with a sufficiently long minority lifetime acts like a linear resistor, the resistance of which is inversely proportional to a self-rectified or externally applied dc bias current. A very small dc current can control a very large RF current in a PIN diode, compared to a P-N junction or Schottky metal-semiconductor diode.

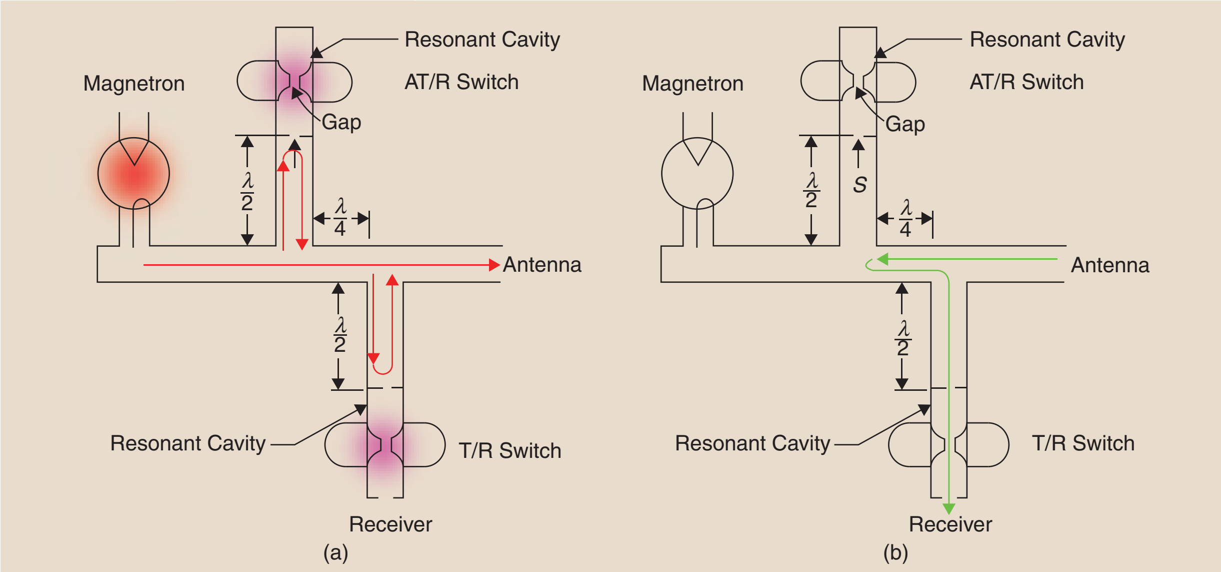

Figure 9. *A typical microwave radar T/R switching arrangement, showing T/R tubes (a) ionized in transmit mode and (b) deionized in receive mode [after 14].*

of the duplexer assembly in the Western Electric AN/APS-4 radar (Navy ASH). This system was built into a pod that hung under the wing of fighter planes. It uses 724B tubes as T/R and AT/R. These tubes are mounted in resonant waveguide cavities to develop high RF voltage for fast ionization. Keep-alive voltage is applied only to the T/R tube. To maintain protection when the radar was turned off, a solenoid-controlled plunger was used to mechanically block the waveguide. The plunger was withdrawn only when the keep-alive voltage was present.

On transmit, the two fired 724B tubes reflect shorts to the waveguide wall, allowing transmitter power from the magnetron to travel to the antenna. The fired 724B in the T/R box blocks RF from entering the receiver. On receive, the unfired cell in the T/R box allows echoes to travel from the antenna to the receiver. With the cell in the R/T box unfired, the full length of the R/T box presents an open to the waveguide, blocking received signals from traveling to the magnetron transmitter. Figure 11 is a photo of the AN/APS-4 duplexer assembly.

A slightly different X-band waveguide arrangement is shown in Figure 12. Here, the AT/R is a 1B35, and the T/R cell is a 1B24. Instead of being mounted in resonant cavities, these T/R tubes are self-contained (see Figure 13). The 1B35 is essentially a gas-filled, fixed-resonant cavity with a sealed glass window in one end for coupling through an opening in the wall of the waveguide. The 1B24 comprises a pair of capacitive cones that combine with the inductance of the housing to make a self-contained resonant cavity with low firing power [16]. The duplexer in Figure 12 was used in the AN/APS-31 and several other airborne radar systems [17].

The X-band duplexers described previously used two low-power klystron oscillator tubes. One was for the local oscillator of the superheterodyne receiver working at the radar frequency. It was locked at a frequency offset from the transmitter frequency by the receiver intermediate frequency via an automatic frequency-control circuit. The second klystron was the local oscillator for the homing beacon signal, which operated on one of a few fixed frequencies several

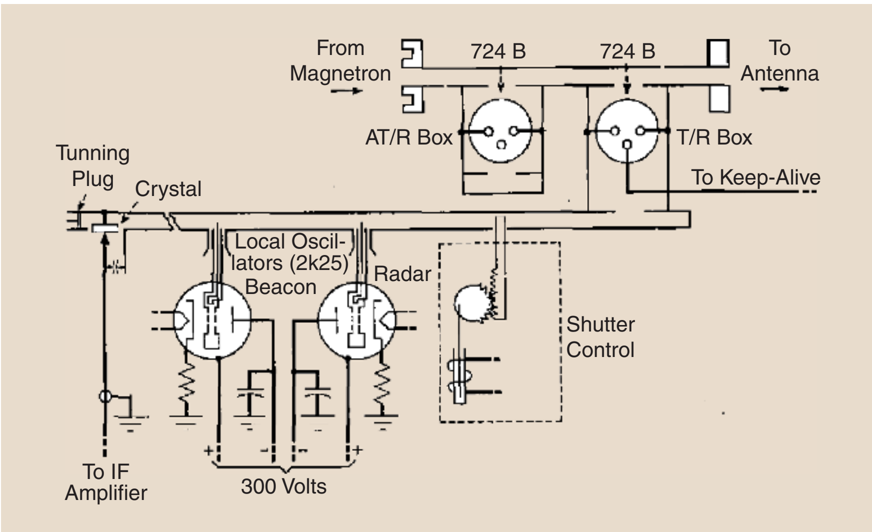

Figure 10. *The AN/APS-4 duplexing arrangement [from 15].*

tens of megahertz below the radar frequency. Because the beacon transmitter could be on an aircraft carrier located miles away, the beacon local oscillator had no local transmitter to track. Therefore, its frequency had to be maintained independently. A phase bridge circuit was used to lock its frequency to that of a temperature-stabilized reference cavity in the 1Q22 family. In some designs, the receiver path had a fairly narrow bandwidth, nominally tuned to the radar frequency. To enable reception of the beacon signal, a solenoid-operated plunger retuned the receiver path to the beacon frequency [15].

Another type of T/R was the broadband design, typified by the X-band 1B63 shown in Figure 14. It is essentially a gas-filled, two-stage waveguide filter with resonators comprising inductive irises and close-spaced conical capacitive gaps to ensure breakdown at low RF power. A dc keep-alive voltage is supplied to the second set of cone gaps. The 1B63 was frequently paired with a member of the 1B35 AT/R family or a

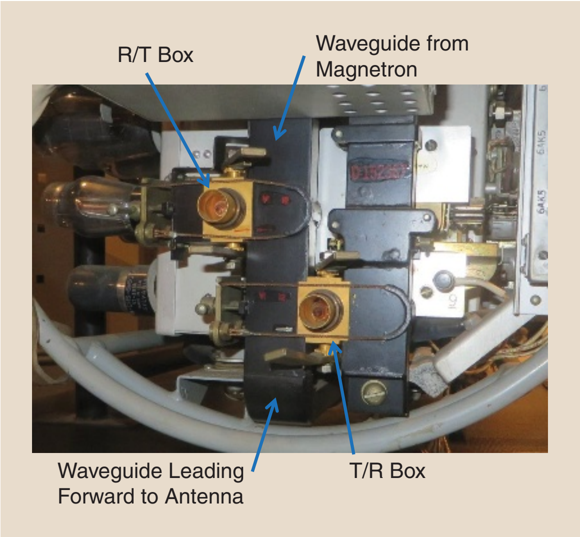

Figure 11. *The AN/APS-4 duplexer, as seen looking forward from the bottom rear of the pod enclosure. Nearly 15,000 of these systems were built by Western Electric. (Photo by the author, 2016.)*

Figure 13. *Self-contained T/R tubes. From left, the Westinghouse-developed 1B24 for X-band, Bomac 1B35A AT/R for X-band, and Sylvania 1B26 for K-band. The RF structure in the T/Rs is within the circular structure, which would be sandwiched between waveguide flanges. The glass structures are gas reservoirs with an insulated feedthrough for the keep-alive voltage. The AT/R is a one-port cavity resonator with a glass coupling window. (Photo by the author, 2016.)*

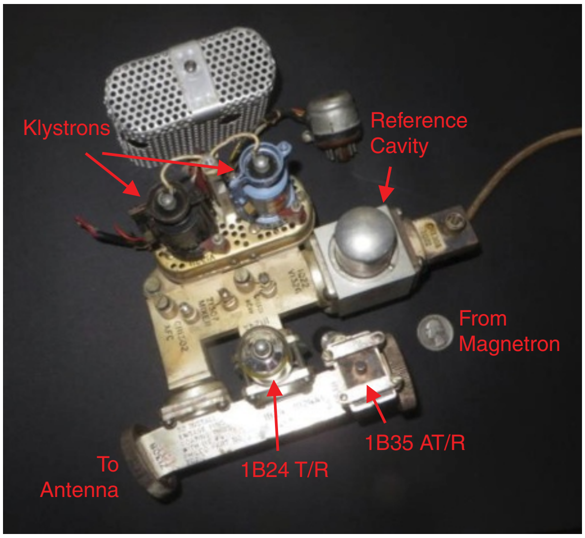

Figure 12. *This X-band duplexer for AN/APS-31 radar uses a 1B24 T/R, a 1B35 AT/R, and two 2K25 klystron local oscillators, one of which is frequency stabilized by a 1Q22 reference cavity. Mixer crystals are mounted in the center waveguide section, and coaxial IF outputs are underneath. (Photo by the author, 2016.)*

Figure 14. *A 1B63A broadband T/R. The round contact at the top is for the keep-alive electrode. (Photo by the author, 2016.)*

pair of such tubes mounted on opposite sides of the waveguide for higher power operation.

For low-power systems, such as the AN/APG-15 tail-gun radar operating at lower microwave frequencies, the lighthouse T/R duplexer was developed (see Figure 15). It uses a medium-power lighthouse triode as the transmitter, a low-power lighthouse tube as the receiver local oscillator, a 1B27 T/R cell, and a 1N21-family crystal mixer diode in a compact coaxial transmission-line assembly. The oscillator cavities are mechanically tunable, while the T/R cavity is tuned by a mechanical adjustment built into the 1B27 itself.

Yet another T/R switch used a pair of T/R tubes in a balanced duplexer arrangement. One basic scheme using quadrature couplers is shown in Figure 16. A pair of T/R tubes between the two couplers allows RF to flow in different directions, depending on whether the tubes are fired or not. Dual T/R tubes (Figure 17) were used in these designs to ensure balanced reflections on transmit and balanced transmission on receive. Similar designs using magic tees and hybrid ring couplers are also possible.

Later Radar Developments

A development from circa 1950 is the polarization twist duplexer, illustrated in Figure 18 [18]. A number of small-diameter T/R tubes are mounted in a helical arrangement inside a circular waveguide. When the cells are deionized, RF travels through the waveguide without changing the direction of the polarization. When the cells are ionized, they act as short circuits to the electrical field, forcing the field to rotate by 90° along the length of the device. The RF, therefore, couples to two different ports, depending on the power level. These duplexers were used in radars operating at power levels up to several megawatts peak power.

Circulators using the nonreciprocal properties of magnetized ferrites were developed in the 1950s. The circulator enabled a different radar front-end architecture. The circulator performs the T/R duplexing function independent of power level. Circulators can be

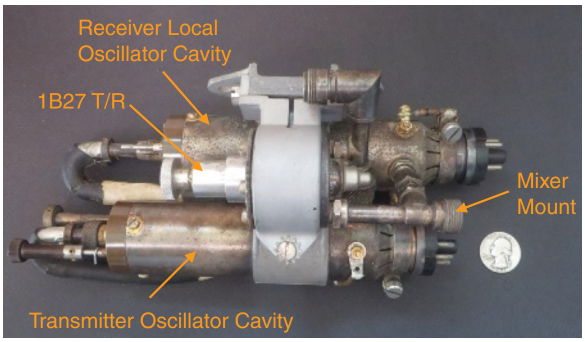

Figure 15. *A lighthouse T/R duplexer, with 1B27 T/R and lighthouse oscillator tubes. The T/R is tuned by manually operating the tuning knob, which changes the capacitive gap inside the tube. (Photo by the author, 2016.)*

In 1936, Robert Page of the U.S. Naval Research Laboratory developed a duplexer based on transmission-line coupling and the behavior of a pair of gridded tubes at the receiver input.

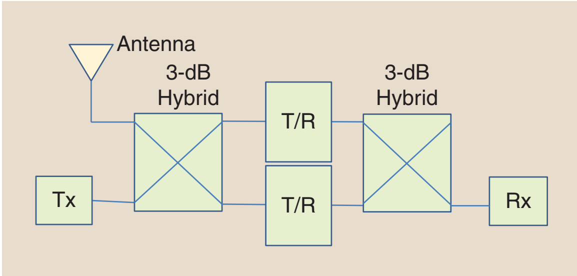

Figure 16. *A balanced duplexer using quadrature couplers and matched T/R tubes. When transmitter (Tx) power is applied, the T/R tubes fire, reflecting the transmitter signal back through the input hybrid coupler to the antenna port. When the T/R tubes deionize, echo signals from the antenna recombine at the receiver (Rx) port of the second coupler.*

Figure 17. *X-band (left) and S-band (right) dual T/R tubes for balanced duplexers. (Photo by the author, 2016.)*

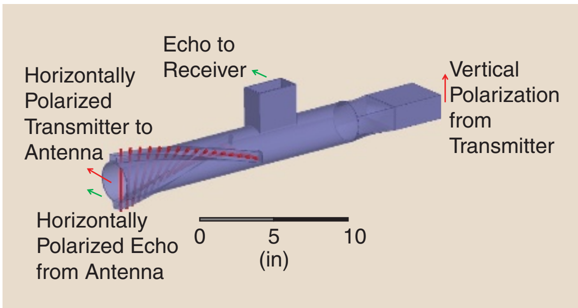

Figure 18. *A polarization twist duplexer. A high-power, vertically polarized wave entering from the transmitter at the right causes the tubes to ionize. This forces the wave to twist to horizontal polarization in the circular waveguide at the left, leading to the antenna. The top waveguide port is cut off for this mode. On receive, a low-level, horizontally polarized echo entering from the left passes the deionized tubes, without changing orientation, and exits to the receiver through the top waveguide port. The transmitter port is cut off for this mode.*

TABLE 1. Examples of 1940s-era radar T/R configurations.

System	Platform/Typical Application	Range (miles) Air	Range (miles) Surface	Frequency (MHz)	Tx	Tx tube(s)	Tx power (kW Peak)	Receiver Front End	Rx Local Oscillator	Antenna	Duplexer/Receiver Protection
Chain Home	Ground/air search	120	–	20–55	Triodes	VT-90 [1] (Br.)	350	Tube	Tube	Bistatic	Hundreds of meters separation
SCR-268	Ground/searchlight	22	–	200	Triodes	VT-127 [2] (16)	75	954 RF amplifier	955	Three	Separation, power tube at receiver input
SCR-270	Ground/search	80-100	–	110	Triodes	WL-530 [3] (2)	200	832 protector/ 1630 [10]	954	Single	Air spark gap, GA-4 spark gap [9]
SCR-270-D	Ground/search	80-100	–	110	Triodes	WL-530 [3] (2)	200	832 protector/ 1630 [10]	954	Single	Air spark gap, GA-5A/ WL-532 spark gap
SCR-270-BB	Ground/search	80-120	–	110	Triodes	WL-530 [3] (2)	200	9002 protector	GL-446A [7]	Single	Air spark gap, GA-5A/ WL-532 spark gap
Radar Mark 1	Ship/fire control	5	5	700	Triodes	WE-388A [4] (2)	2	WE-703A mixer	WE-316A	Single	Reflection from overloaded RF amplifier tube
Radar Mark 3	Ship/fire control	25	12-20	700	Magnetron	WE-700 series [5]	40	WE-703A mixer	WE-316A	Single	WE-702 spark gap [11]
ASB	Air/search	6	30-40	550	Triodes	15E [6] (4)	5	955 or 6AC7 GL-446A [7]	955 GL-446A [7]	Single	1960 spark gap [12]
AN/APG-15	Airborne/rear gun sight	1	–	2,500	Lighthouse	2C43 [7]	0.75	Crystal mixer	2C40 [7]	Single	LHTR, 1B27
AN/APS-4 [13]	Air, search/intercept	5	25-50	9,375	Magnetron	725A [5], [8]	35	Crystal mixer	723A/B	Single	724B AT/R, T/R
AN/APS-31	Air/search	to 200	–	9,375	Magnetron	4J52 [8]	70	Crystal mixer	723A/B	Single	1B35 AT/R, 1B24 T/R
SCR -584 [14]	Ground/search, track	20-35	–	2,700–2,900	Magnetron	2J32 [8]	300	Crystal mixer	417A	Single	721A spark gap

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Tx: transmitter; Rx: receiver.

realized in Faraday rotation structures [19], [20], four-port differential phase-shift circuits [20], or three-port junctions in waveguide or stripline [21]. Although the circulator performs the T/R function, the receiver still needs to be protected from high-power RF from transmitter reflections due to imperfect antenna matching or close-in reflectors, imperfect isolation in the circulator, or external high-power RF sources. Receiver protection is accomplished by a separate limiter, which today is essentially a modern version of the earlier T/R tube.

Investigations of the use of semiconductor diodes as microwave switches [22] soon led to the use of diodes as limiters [23]. The combination of a T/R tube with a diode limiter (T/R-limiter) is commonly known as *TRL*. The diode is typically a PIN device for high power handling. A diode limiter was added to a balanced duplexer for improved receiver protection in 1964 [24]. Diode limiters were also used to overcome the high spike leakage due to slow turn-on in ferrite limiters in 1971 [25]. An all-solid-state design consisting of a microstrip or stripline junction circulator or solid-state switch and a PIN diode limiter is the modern T/R module approach.

Salient details of representative radar systems and additional hardware references are provided in Table 1.

Final Thoughts

It is remarkable to realize that practical microwave radar systems were developed fewer than 20 years after the first commercial radio broadcasts. Transmitting tubes transitioned from low-power triodes to high-power cavity magnetrons. Operation advanced from a few tens of megahertz using gridded tubes and open-wire transmission lines to over 10,000 MHz using klystrons, magnetrons, and waveguides. High-power modulators went from mechanically driven spark gaps to thyratrons. All these occurred in the short time between 1935 and 1945 and all before the invention of the transistor.

Aside from an occasional selenium or copper oxide power-supply rectifier, the only solid-state devices in those early radars were cat-whisker silicon diodes that were so sensitive they needed special protection from the high-power RF produced by the transmitter. Today, lighthouse and doorknob tubes with power ratings of a few watts have been replaced by transistors. High-power, single-point sources such as the magnetron and traveling-wave tube are being replaced by phased arrays that use silicon, gallium arsenide, and gallium nitride transistors. Beamsteering can be performed electronically—no moving parts. Much of the RF and video switching in a system functionally equivalent to the mechanically switched ASB radar can now be accomplished in a single monolithic microwave integrated circuit chip, with significantly increased performance, reliability, and lifetime.

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